THERMAL ANALYSIS OF A CARBIDE COATED CUTTING INSERT USING COMSOL®

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Abstract. *During the turning process, a considerable amount of the machine energy is transformed into heat near the surface of the cutting insert. Almost all the technical and economical problems of the process are directly or indirectly caused by the generation of this heat. In the past few years, tool inserts have been coated with materials that provide minor wear with thermal insulation features, aiming to increase the tool life. Determining the cutting temperature during the turning process is one of the most important factors to understand the turning tool performance. Thus, it is important to develop efficient methods to determine this temperature. This work proposes to simulate the heat phenomenon, in transient regime, of a cutting tool considering the presence of the coating, convection and radiation. The results showed the coating effect for different coating thickness values. Numerical and experimental results are compared to validate the methodology.*

Keywords*: Thermal analysis, COMSOL, Cutting insert, Coating.*

1. NOMENCLATURE

T	Temperature,°C
T_∞	Room temperature, °C
x,y,z	Cartesian coordinates, m
t	time, s
h	Heat transfer coefficient, $Wm^{-2}K$
q_0''	Imposed heat flux, Wm^{-2}
T_{CI}	Temperature on the chip-insert interface, °C
T_{CS}	Temperature on the cutting-substrate interface, °C
$\Delta T_{UNCOATED}$	T_{CI} - T_{CS} for the uncoated insert, °C

Greek symbols	
k	Thermal conductivity, $Wm^{-1}K$
α	Thermal diffusivity, ms^{-2}
ε	Emissivity
η	the outward drawn normal to the surface
σ	Stefan-Boltzmann constant, $Wm^{-2}K^{-4}$

2. INTRODUCTION

A considerable amount of the consumed energy in the turning process is transformed into heat near surface of the cutting insert. Most of the technical and economical problems of the process are directly or indirectly caused by the generation of this heat. With an increasingly competitive market, higher cutting speeds and higher feed rates are used in machining processes aiming to increase productivity. Using higher cutting speeds and higher feed rates more heat is generated during the process, damaging the insert performance (Trent and Wright, 2000).

In the past few years, the tool inserts have been coated with materials that provide minor wear with thermal insulation features. The first feature is that it makes the major part of the heat generated during the process go to the chip. The second is that it reduces the insert wear. Both are responsible to increase the tool life of the cutting insert.

Determining the cutting temperature during the turning process is one of the most important factors to understand the turning insert performance. However, due to the movement of the workpiece and difficulty of accessing regions, even in simple machining conditions, the determination of the temperature in the insert-chip interface is troublesome. Thus, it is important to develop efficient methods to determine this temperature.

The first documented work relating to the temperature study during the turning process of metals was conducted by Thompson (1798). The author examined the mechanical equivalent of heat during the drilling process of a brass workpiece. Later, Taylor (1907) recognized the influence of the heat in his article "On the art of cutting metals". Taylor's studies were crucial for the development of the high speed steels. Therefore, the quantitative and precise determination of temperatures during the metal cutting process in terms of measure was first conducted by Shore (1925), Gottwein (1925) and Herbert (1926) almost at the same time. These authors measured the temperature in the process using thermocouples. Several methods have been proposed to determine the temperature since then. Some authors used analytical methods to solve the thermal problem (Rapier, 1954; Young and Chou 1994), whereas others used experimental methods (Boothrouyd, 1961; Shaw, 1984; Stephenson,1991; Carvalho *et al*., 2006; Mitsuichi *et al*., 2015).

Insert coating appeared in the 1960's due to the advance in the field of materials. In the beginning, the inserts were coated by the CVD process (*Chemical Vapour Deposition*) and later on by the PVD process (*Physical Vapour Deposition*). Nearly 80% of the turning processes are carried out using coated inserts (Balzers, 2002). Ruppi *et al*. (1998) studied the one layer coating properties of TiC, TiN, TiCN and Al_2O_3. These inserts were used for turning hardened steels and steels. Grzesik and Nieslony (2004) showed that depending on the type of coating of the cemented carbide insert, the contact area at the chip-insert the average temperature at the interface is modified. Rech *et al*. (2005) concluded that the coating is not a thermal barrier in continuous cutting processes, but only in interrupted cutting process especially at high cutting speeds. Brito *et al.* (2009) studied the coating influence in the cutting insert considering its thickness variation. They utilized cemented carbide and diamond substrate and TiN and Al_2O_3 coatings. The coatings did not show satisfactory results in continuous cutting process. Brito *et al*. (2015) continuing the work of Carvalho *et al.* (2006) and Brito *et al*. (2009) proposed a more complex geometry to represent the numerical model of the turning problem. To solve this problem, the authors used a nonlinear inverse heat conduction technique with the commercial software COMSOL®.

The COMSOL *Multiphysics* is FEA software (Finite Element Analysis) based on advanced numerical methods to model and solve physical problems. Gerlich *et al*. (2013) presented a software validation for a calculation of heat transfer in buildings. The heat transfer calculation in the COMSOL *Multiphysics* was validated by the comparative verification provided by the International Energy Agency and by the comparison with measured data in real building segment. Greiby *et. al*. (2013) used an ordinary least square and a sequential estimation method in MATLAB with COMSOL to sequentially estimate a temperature-dependent thermal conductivity of a cherry pomace. Suarez *et al*. (2013) studied the heat transfer in solids using infrared photothermal radiometry and simulation using COMSOL *Multiphysics*. The good agreement between the results of numerical simulation and experimental data showed the potential of the software for the interpretation of photothermal experiments.

3. THEORICAL FORMULATION

3.1 Problem description

The numerical thermal model is a coated and uncoated carbide cutting insert with the same dimensions, presented in Fig.1 and Fig.2. These two numerical models are used in the simulation to compare the coating effect on the thermal gradient created in the insert during the cutting process. The insert geometry used is from Brito *et al*. (2015). Both models are subject to the boundary conditions of imposed heat flux, convection and radiation.

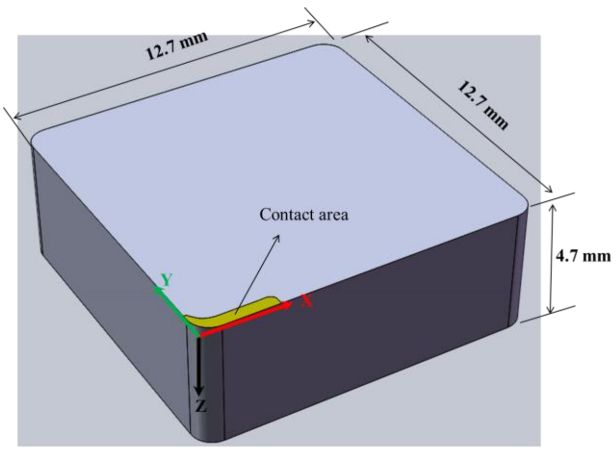


Figure 1. Uncoated insert.

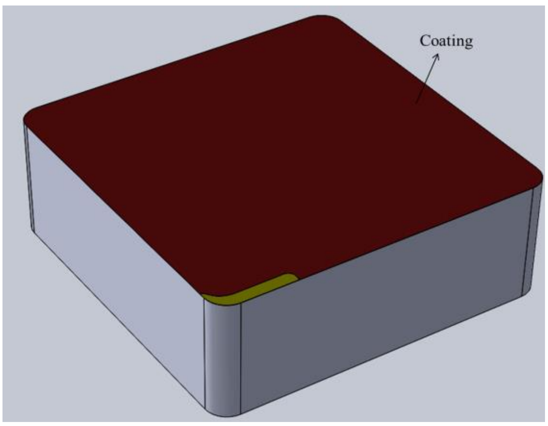
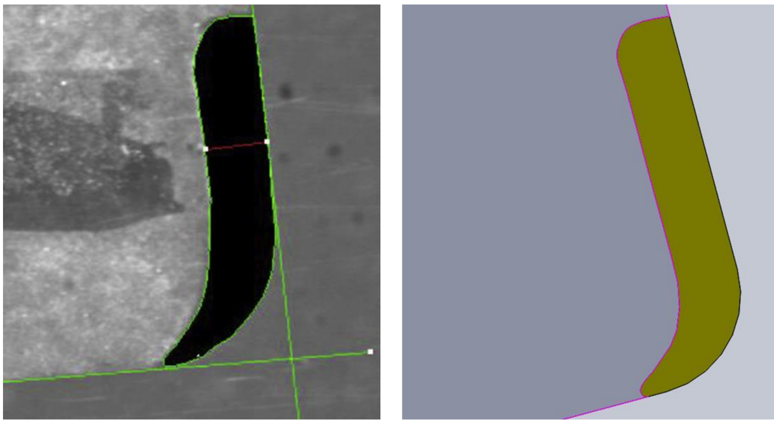


Figure 2. Coated insert.

The contact area is the contact interface between the insert and the workpiece, where the heat flux is applied during the cutting process. The other insert surfaces, which are in contact with the air, are subject to constant convection and radiation. In order to measure the contact area, an image system program with video camera Hitachi CCD, KP-110 model, an AMD PC- K6 450 MHz and the GLOBAL LAB image software were used by Carvalho *et al*. (2015). The experimental contact and the numerical contact area of this work are presented in Fig.3a and b.



a) b)

Figure 3. a) Image treatment of the experimental contact area and b) numerical area on the computational model.

The thermophysical properties for the substrate and the coating (Tab.1) were obtained from Brito *et al.* (2015), Grzesik *et al*. (2009) and Yuste *et al*. (2010). All the thermalphysical properties were considered constant and also some simplifying hypotheses were adopted such as: perfect thermal contact between the substrate and the coating, constant medium temperature and no internal heat generation in the substrate and the coating.

Table 1. Thermalphysical properties of the substrate and the coating of the material.

Element	k	c_p	ρ	ε
Carbide substrate	87	225	14950	0.80
TiN	21	4650	645	0.22

The thermal problem presented is a direct problem, having all boundaries and initial conditions known. The heat flux, the convection coefficient and the initial temperature are extracted from Brito *et al*. (2015). The equations to solve the models are shown as follows.

3.2 Thermal model

The thermal model may be described by the transient three-dimensional diffusion equation:

$$\frac{\partial^2 T}{\partial x^2}(x,y,z,t)+\frac{\partial^2 T}{\partial y^2}(x,y,z,t)+\frac{\partial^2 T}{\partial z^2}(x,y,z,t)=\frac{1}{\alpha}\frac{\partial T}{\partial t}(x,y,z,t) \tag{1}$$

Subject to the following boundary conditions of convection and radiation:

$$-k\frac{\partial T}{\partial \eta}(x,y,z,t)=h(T-T_\infty)+\sigma\varepsilon\left(T^4-T_\infty{}^4\right) \tag{2}$$

In the contact area, the boundary condition of imposed heat flux is:

$$-k\frac{\partial T}{\partial z}(x,y,0,t)=q_0'' \tag{3}$$

The initial condition of temperature used for the entire domain is as follows:

$$T(x,y,z,0)=T_0 \tag{4}$$

3.3 Numerical solution

The diffusion equation presented in section 3.2 is solved by using the commercial software *COMSOL Multiphysics* 5.2®. The software divides the geometrical domain into smaller parts and applies the equations that rule the problem to these parts. The insert geometry was designed by CAD software and later exported to COMSOL.

The heat flux at the contact area was estimated by Brito *et al.* (2015) using the Specification Function method. The average coefficient of heat transfer by convection adopted was 20 W/m^{2}K, while the initial temperature utilized was 31.06ºC.

4. EXPERIMENTAL PROCEDURE

4.1 Emissivity determination

To determine the emissivity of a cemented carbide tool, a controlled experiment was carried out in the Heat Transfer Laboratory (LabTC) at the Federal University of Itajubá (UNIFEI). The data acquisition Agilent 34980A, a digital power supply MCE 1051, a thermographic camera FLIR T450sc , a 50x50x0.25 mm resistive Kapton heater, a carbide cutting insert and thermocouples type K were used for these experiments. Figure 4 presents a picture of the experimental setting used for this experiment. To accomplish the experiment, the insert are heated on one surface by the resistive heater connected to the power supply MCE 1051. The surface is subjected to loss due to convection and radiation until they reach the permanent regime. The temperatures of the insert are measured through the use of the data acquisition controlled by a PC. When the steady state is reached, the emissivity is checked by comparing the temperature measured by the thermography camera FLIR T450sc and the temperatures indicated by the acquisition. The temperature of the sensor is adjusted to the temperature of the sample through the variation of the emissivity of the material.

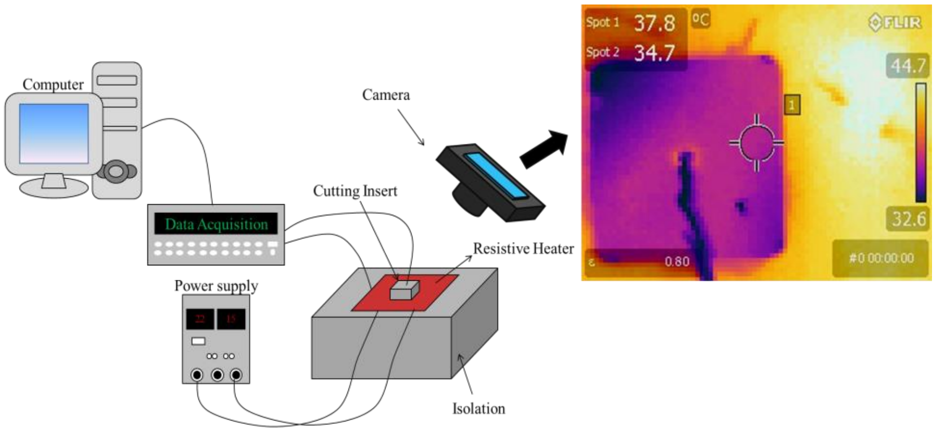
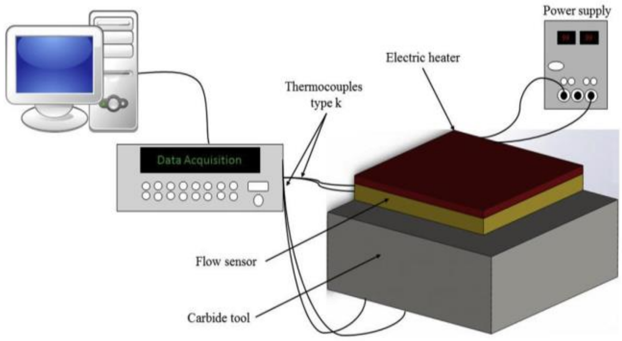


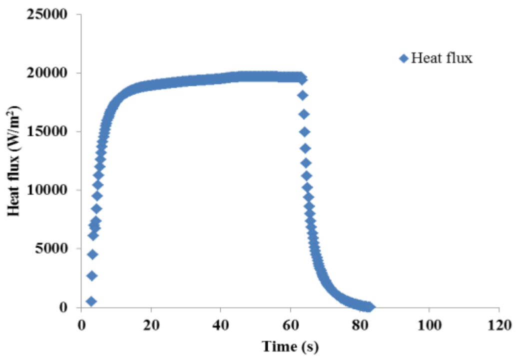
Figure 4. Experimental apparatus for the calculation of the emissivity.

5. VALIDATION OF THE METHODOLOGY

In order to validate the methodology a controlled experiment (Fig. 5a) was carried out by Brito *et al.* (2015) using a cemented carbide insert with dimensions of 0.0127 x 0.0127 x 0.0047 mm. A heat flux transducer and two thermocouples previously calibrated and a kapton electric heater were used on this inserl. This heater was connected to a digital power supply (MCE). The heat flux transducer was located between the heater and the insert in order to measure the heat supplied to it (Fig. 5b). The heat flux and temperatures signals were acquired by a HP Series 75000 data acquisition system, controlled by a PC. Temperatures were measured by using type K thermocouples (30 AWG) welded by capacitive discharge and calibrated by using a bath temperature calibrator ERTCO with a stability of ±0.01ºC.



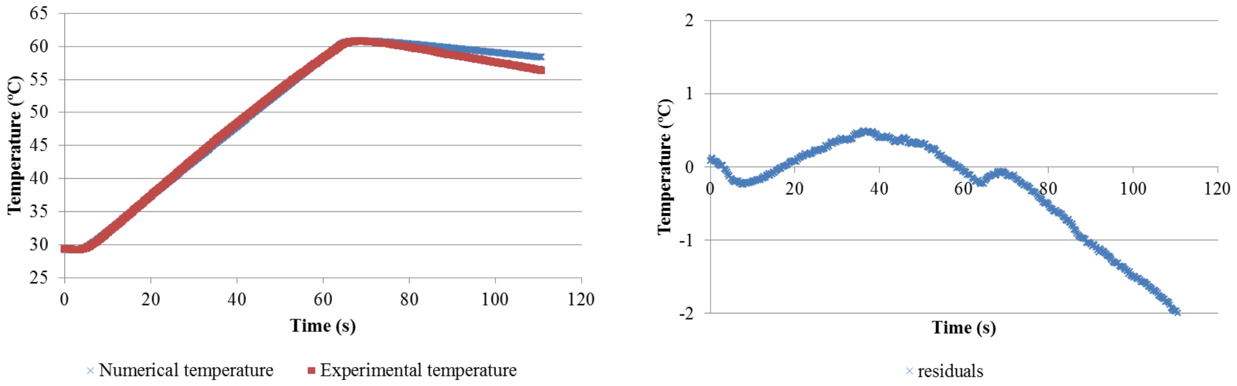
a)



b)

Figure 5. a) Sketch of the experimental apparatus used in the validation from Brito *et al.* (2015) and b) Experimental heat flux measured.

One improvement of this work is the presence of the radiation which was not considered at Brito *et al*. (2015). In Fig. 6a the comparison between the numerical and experimental temperature of the insert used in the test is showed, whereas Fig. 6b presents the temperature residuals.



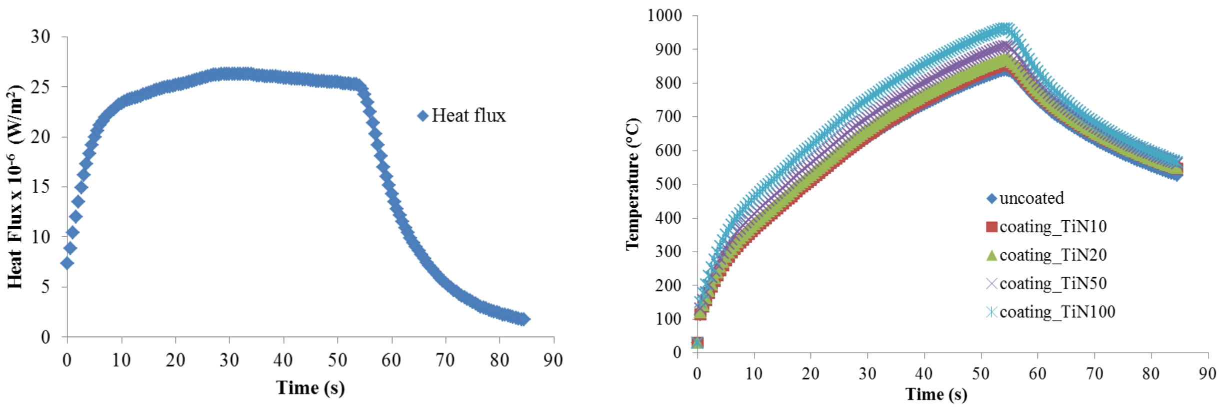
a) b)

Figure 6. a) Numerical and experimental temperatures, and b) Temperature residuals.

6. RESULTS

In order to investigate the temperature distribution for a time interval *t* during the turning process, simulations of the uncoated and coated insert have been performed. The main objective is to analyze the thermal influence of the heat flux on the thickness variation of coated cutting inserts. The coating adopted in the simulation was Titanium Nitride (TiN) with thickness of 10, 20, 50 and 100 µm. In the coated insert simulation two numerical probes were used to measure the temperature, one placed on the chip-insert interface and the other on the coating-substrate interface. For the uncoated insert simulation, five numerical probes were used keeping the same numerical probes coordinate *z* position of the coating insert simulation (z = 0, -10, -20, -50 and -100 µm). All the probes for the uncoated and coated simulation have the same position for the other coordinates (x = 2 mm and y = 0.25 mm).

Figure 7a presents the heat flux used to calculate the temperature in the simulations. This heat flux has the duration of 84.5 s with a time interval of 0.5 s. In the first ten seconds the heat flux intensity increases abruptly. In 10 to 55 seconds, the heat flux stays stable. From this point, the heat flux intensity decreases up to the final instant, once the turning process was interrupted. Figure 7b shows the comparison of the temperature on the chip-insert interface between the uncoated insert and the coated insert for different thickness coating.



a) b)

Figure 7 - a) Heat flux adopted in the simulation and b) Comparison of the temperatures on the chip-insert interface.

It can be observed in the figure 7b that the temperatures for the coated insert, for all the thickness coating, are higher than the temperature for the uncoated insert. Thus, the coating holds the heat and protects the substrate. For better understand it, Fig 8 to 11 presents the difference of the temperature on the chip-insert and coating-substrate interfaces for each thickness coating of the coated insert and compare it with the uncoated insert. In table 2 the maximum temperature, instant 54.5 s, for all cases is presented.

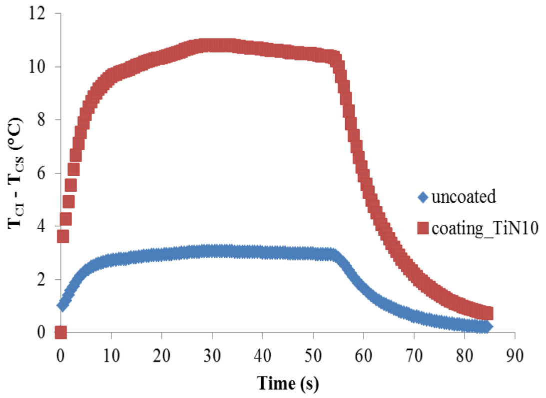


Figure 8. 10 µm coating insert x uncoated insert

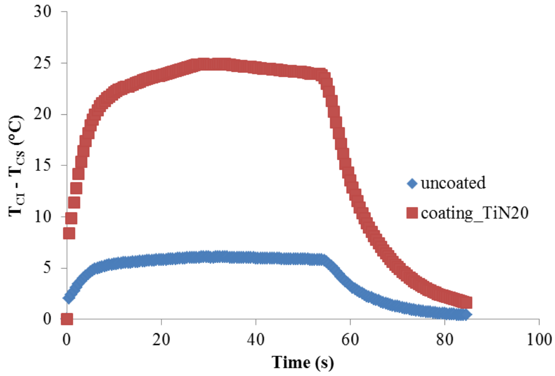


Figure 9. 20 µm coating insert x uncoated insert

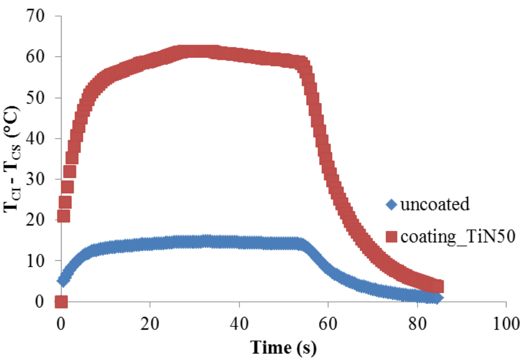


Figure 10. 50 µm coating insert x uncoated insert

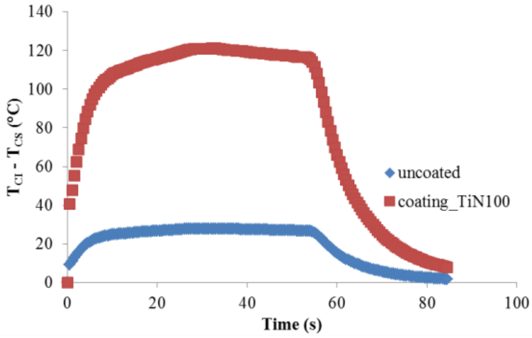


Figure 11. 100 µm coating insert x uncoated insert

Table 2. Numerical results obtained from the temperature values at instant 54.5 s.

Coating	T_{CI} (°C)	T_{CS} (°C)	T_{CI} - T_{CS} (°C)	$\Delta T_{UNCOATED}$ (°C)
10	857.94	847.73	10.21	2.88
20	871.36	847.85	23.51	5.72
50	909.84	852.19	57.65	13.87
100	961.94	847.89	114.05	26.30

It can be verified in the table 2 that even for tiny thickness coating there was an increase in the temperature difference (T_{CI} - T_{CS}) when compared to the uncoated insert. The usual value for the coating thickness of a cutting insert is between 10 to 20 µm. For greater values of the thickness coating, 50 and 100 µm, this difference is even larger. Figure 12 presents the simulation results for the uncoated insert, whereas Fig. 13 shows the simulation results for the coated insert with different coating thickness.

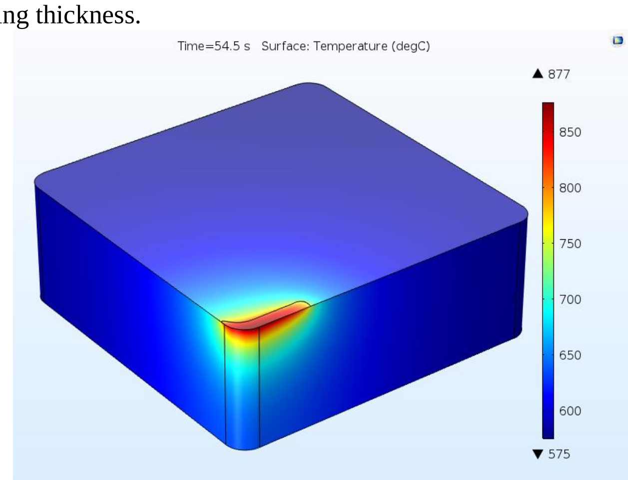
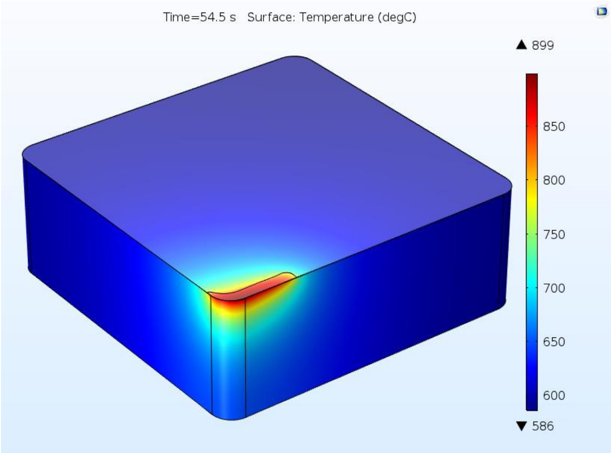
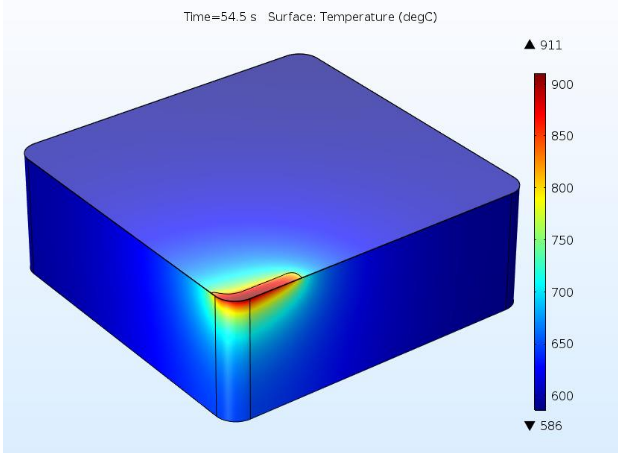


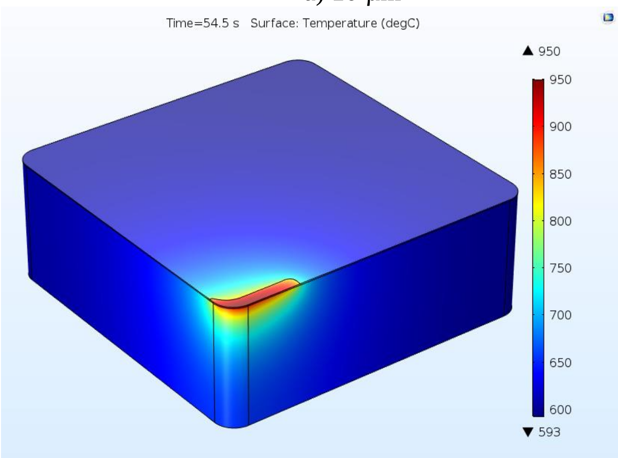
Figure 12. Temperature field of the uncoated insert.



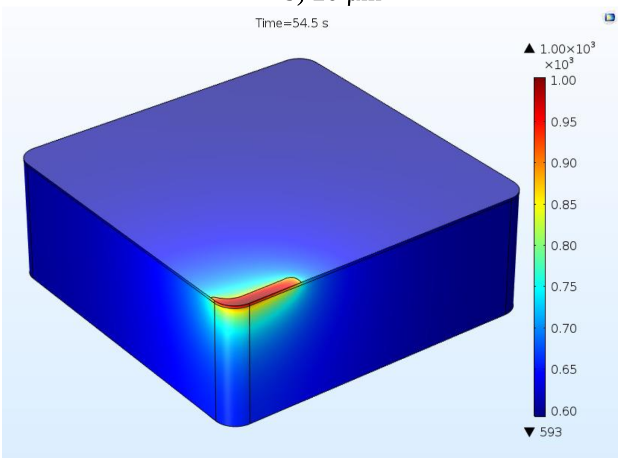
a) 10 µm



b) 20 µm



c)50 µm



d) 100 µm

Figure 13. Influence of the coating thickness variation on the temperature field.

In the Fig. 12 it can be seen the heat penetrating the substrate and increasing the temperature. In the Fig. 13, it is possible to see that the greater the thickness of the coating, more the coating holds the heat on the top surface and protects the insert substrate (red region in the figure).

7. CONCLUSIONS

This work presented the coating effect on the temperature field of the cutting insert. For all the models with different coating thickness, the results presented the expected behavior, once less heat was transmitted to the substrate. One improvement of this work is the presence of the radiation, not considered in previous works. The good agreement between the results of numerical simulation and experimental data (Fig. 6a and b) showed the potential of the COMSOL when applied to the resolution of thermal problems in turning.

8. ACKNOWLEDGEMENTS

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